FAYE ON THE LAWS OF STORMS*

Mechanical Identity of Waterspouts and Eddies.—The question then is reduced to this, viz., whether, when in the middle of the most profound calm these destructive waterspouts are seen to appear, the form of which corresponds so well to the eddies formed in streams of water, we can point to any current by which the phenomenon has been originated. Now this is precisely what we intended to set in strong relief in describing the general currents of the atmosphere. The counter-trades clearly show that there exist above our heads unmistakable currents of air in motion. Without even recurring to considerations of this nature, it is enough to cast our eyes over the heavens on the appearance of a waterspout, in order to see by the march of the clouds that in spite of the calm below, powerful horizontal currents prevail aloft, which, as their different parts cannot advance at the same rate, must consequently give rise to whirling movements of a more or less decided character. If one of these whirls meet with the favourable circumstances so often seen in water-streams, it will be regularly developed by taking the form which analysis assigns to it; by its downward movement it will even penetrate through into the calm strata, the resistance of which will gradually alter its form and its course, and end by reaching the ground. This simple notion of the mechanical identity of gyrations, whether of liquids or gases, furnishes at once the explanation of phenomena which meteorologists have laboured to find in an entirely different range of ideas. Waterspouts contain powerful forces in action, because they draw the force from a medium above, where it is in abundance; they march onwards because they follow the current which originates them; at their base they are slightly curved, not forwards but backwards, because the comparatively still medium they traverse offers a certain amount of resistance; they act nevertheless in the same manner both on the ground and over water, whatever be the curvature of the conical tube which descends from the clouds, because this curvature never interferes with the direction of the axis of rotation of each spiral, but only with the succession of these spirals in space, &c.

This identity of waterspouts in air and of eddies in water, which is so complete in a mechanical and geometrical point of view, is no longer to be looked at altogether from the physical standpoint, on account of the differences which in this respect exist between water and gas. Indeed, the temperature of a stream of water is almost the same at all depths; in the air, on the contrary, heat decreases markedly as we rise to the higher strata. Further, the moisture of the air is liable to be condensed for a fall of temperature often very slight. Thence the cold air of the high regions, drawn gradually downward by the whirling movement into the low and moist strata, generates a thin mist all round the waterspout. This mist serves as an outer envelope or sheath, the form of which is more or less sharply marked, being rendered visible by its opacity. There is no doubt that the air in its descent is subjected to an increasing pressure and gradually rises in temperature; but it is lower than the temperature of the surrounding air, and it is enough if it falls to the dew-point of the general mass of air surrounding it in order that the nebulous sheath may be immediately produced. If the difference of the two temperatures is insufficient, or if the humidity is too low in any particular stratum, the misty sheath will not be formed, and the waterspout will in part be invisible. None the less, however, will it be there, though it seem cut in two, or appear only in its upper part in a truncated form. This is the appearance so often presented by waterspouts at their commencement, when the upper and lower portions are seen, but not the intermediate portion. Soon these detached portions meet, the outside sheath completing itself as the stratum traversed by it becomes slightly more humid, or as the air whirled more rapidly downwards by the waterspout becomes slightly colder than the air it meets.

Just as happens in the case of the water which gradually descends down an eddy in its whirling course, the air, which gradually descends with a violent whirling motion down the waterspout, escapes from it on coming into contact with the ground, and thereafter rises again in an irregular manner outside the waterspout. But the volume of air which enters into ordinary waterspouts is far from being sufficient to give rise, at a distance, to a wind of any appreciable force; it is only in proximity to and immediately around the base of the waterspout, where this irregular upward movement of the air manifests itself by the ascent of the dust or spray already raised by the lower spires of the meteor. The base of the waterspout is then enveloped in a sort of confused cloud ceaselessly renewed, unless the end of the waterspout ceases to reach down to the ground. This is especially the case when a waterspout suddenly meets a valley in its course; its lower end goes on lengthening, and with little delay is again joined with the ground; but if the movement of translation is too rapid, it will not resume its destructive work till it has cleared the valley and gained the opposite higher ground. Thus in gases as in liquids, whirling movements observe exactly the same laws. The idea is simple and clear: let us, then, without hesitation, put it in place of that of an aërial column with boundaries formed doubtless of misty vapour, but really treated as solid and impenetrable like the crystal spheres of antiquity, through which the cloud draws up the water of the sea, trees, and other objects; or, to put it differently, through which a centripetal updraught violently draws skywards sea-water, trees, &c. In accordance to our idea, all becomes clear and simple in the history of waterspouts; with prejudice, on the other hand, all remains astounding, incomprehensible, and contrary to the simplest notions of mechanics. There, are, however, two points of detail yet to be discussed: we have to return to the appearances from which eye-witnesses have drawn such remarkable conclusions, and to the part played by electricity, a force which meteorologists, till quite recently, were always so ready to resort to in the explanation of phenomena.

As the purely physical appearances of waterspouts differ widely from each other, some have failed to observe the slightest trace of an internal movement; others have attributed to them a descending movement without rotation; and lastly, others, and these the most numerous attribute to them a whirling ascending movement. A little reflection easily explains these contradictions. What is seen and what is related by eye-witnesses whose impressions are vitiated by old-standing prejudice, has no reference to the waterspout itself, which, like air, is transparent and invisible, but to its external envelope of mist, which is more or less opaque. The envelope is exterior, we repeat; it does not therefore partake in the internal gyrations, which, moreover, are too rapid to be visible. Only the surrounding air which is brought into contact with the waterspout is rapidly drawn from some distance by lateral communication with the whirling movement, the result of which is a sort of whirling or spiroidal agitation in the outside sheath of the waterspout. The degree in which movements of this sort favour illusion is well known. It is thus that the slight movements of the cilia of rotifers have the appearance of a rapidly revolving wheel, and the simple rotation of a spirally-cut cylinder of glass produces the impression of a flowing stream of water. Further, the air which is thrown out at the base rises again outside the waterspout. The aqueous vapour imperfectly condensed in the outside of the sheath has itself an ascending tendency sufficient to raise some of the small cloudlets of mist found there. Here are the real movements, complex and changing, but slow enough

* Concluded from vol. xii. p. 538.

to be visible. The illusion of the observer lies in attributing to the interior of the waterspout the movements which really take place round and outside its exterior margin.

The part played by electricity has been thus stated by Peltier, who supposed he had detected traces of this force in the well-known waterspout of Monville. The sheath of vapour is in some sort a continuation of the electrically-charged clouds; it forms a long conductor of about eight hundred feet between the clouds and the ground, a conductor doubtless very imperfect, but on a great scale, and capable of affording to some extent a passage to the electricity. It is, however, far from being comparable with the destructive characteristics of the thunderbolt. The way in which trees overturned by whirlwinds are sometimes broken up has been recognised as resembling more or less that of trees struck by lightning and shattered into splinters; but this effect is only the result of the violent torsion exerted by the gyratory movement of the whirlwind, and not of the sudden passage of an electrical current. Men and animals have often been caught by whirlwinds and injured, without ever experiencing the least electrical shock.

Thus the essential characteristic of these remarkable movements which produce waterspouts or great tornadoes is a circular gyration, the spirals being slightly inclined to the horizon. Wherever you make a section of it, you only find there concentric circles with the radii always converging towards a centre. In representing them geometrically you need not hesitate between the circular diagrams of Reid, Redfield, and Piddington, and the diagrams with converging rays of some learned meteorologists, the victims of a hypothesis and old prejudice. The former diagrams reproduce the mechanical phenomenon in its essentials; the latter answer to a mere illusion which a little reflection should ages since have exploded.

Extension of this Identity to Cyclones.—The last step only remains to extend these conclusions to great tornadoes, that is, typhoons, and lastly to cyclones, which often overspread a vast extent of territory. It is one of the characteristic properties of the eddies generated in currents of water, that they are formed on every scale, even the largest, without undergoing any essential change. Eddies may be a few inches in diameter, a few yards, a few furlongs, or even of still larger dimensions; it is the breadth of the currents where they are generated which alone limits their size. In the ocean there are gyrations on a still vaster scale, or even on a scale altogether colossal, such as the vast currents of the Atlantic which circle round the calm region of the Sargasso Sea. The sun presents the phenomena of whirling movements still better defined and of all dimensions, from large openings equalling our cyclones, even to those large spots which are five or six times greater than the earth itself. In like manner, in the whirling movements of our atmosphere are found small, short-lived eddies of a few feet in diameter, whirlwinds and waterspouts, which last longer, from 10 to 200 yards across, and tornadoes from about $\frac{1}{3}$ to $1\frac{1}{2}$ mile in diameter. Beyond this the eye cannot take in the forms of the whirling columns; these receive another name, but in all essential points they remain the same. When the dimensions are still greater, the diameters measuring 300 miles and upwards, they bear the name of hurricanes or cyclones; but notwithstanding this, their mechanism remains unchanged. They are always gyratory, circular movements increasing in velocity as they near the centre; are generated in the upper currents of the atmosphere, through the inequalities of their velocities; are propagated downwards through the lower strata in spite of the calm or independently of the winds which there prevail; ply their destructive energy when they reach the obstacle offered by the ground; and follow in their march the upper currents, so that the track of their devastations marks out on the surface of the globe the route of the viewless currents of the upper regions of the atmosphere.

There is, however, a difference between whirlwinds and tornadoes on the one hand, and typhoons and hurricanes on the other. As regards the former, note in the first place, the upper portion (*embouchure*), which is a sort of truncated cone inverted and very much widened out above, and in the second place the descending column which prolongs the meteor even to the ground. If the atmosphere was a gaseous mass of air of indefinite height like that of the sun, cyclones would always present these two features. As regards cyclones, however, the ground is very near in proportion to the extent of area they cover, and is reached before they can be subjected to the prolonged contracting process seen in waterspouts and whirlwinds. A cyclone is then a vast whirlwind, but reduced by the obstacle offered by the ground, to the upper part, or to what may be called the funnel-shaped portion of the phenomenon strictly so called. Thence, doubtless, the constant presence in the former of a calm space about the centre, of which the analogue is to be found only in the circling movements of the ocean on their grandest scale; and thence also certain important peculiarities of cyclones to be more particularly insisted on, after having examined the movements of translation of these phenomena.

Course of the Upper Trade Winds.—When the attention is directed to whirlwinds which appear most frequently to be accidental phenomena of short duration and merely superadded to other phenomena of a more general character and much more lasting, it must be allowed that the short lines marking out their course have scarcely been studied from a geographical point of view. These lines probably follow no simple law. In this respect it is otherwise with cyclones; their course recurves, as we saw at the beginning of these articles, on the globe in accordance with a particular law the constancy of which Fig. 2 (vol. xii. p. 402) reveals at a glance. From this chart, the upper currents, whence cyclones derive their origin and mechanical power, do not proceed directly from the equator to the poles. They are deflected at the outset toward the west, then toward the east, thus describing over the surface of the globe parabolic curves whose apices lie somewhere within a few degrees of the polar limits of the surface trade-winds. Clearly these upper currents, which are true aërial rivers, ought to form a part of the upper trades whose existence is assumed, but their actual course is not directly known. If this assumption be correct, then Fig. 2 presents at once the projections of the double system of trades and counter-trades over both hemispheres; and it only remains to explain the singular recurving course taken by the upper trades. This explanation we shall attempt, though the question lies a little out of our way.

If the atmosphere were withdrawn from the influence of the solar heat, it would remain in equilibrium; its successive strata would arrange themselves according to surfaces of level, and would become part and parcel, so to speak, of the solid globe itself; at least it would, even as regards the highest strata, exactly follow the earth's rotation. The effect of the solar heat is constantly to disturb this equilibrium, by the introduction of movements which are the more curious inasmuch as they do not essentially destroy the normal stratification of the strata of the atmosphere. The air incumbent over the hemisphere actually facing the sun is expanded in its lower strata, where the opacity arising from dust floating in the air, and above all the aqueous vapour, absorbs a large part of the heat-rays of the sun. The intervention of this aqueous vapour which ascends vertically from stratum to stratum, has in a special manner the effect even of rendering the diurnal variation of temperature perceptible at heights at which it would not be felt if the air was dry. The maximum of

this general dilatation in the torrid zone takes place under the vertical rays of the sun. In this manner the centre of gravity of the lower strata rises vertically; these raise the strata above them, which being specifically lighter, dry and transparent, are consequently less sensitive to the sun's rays. All the strata in succession, thus thrust upward above their surface of normal height, tend to flow with accelerated motion along these surfaces in the direction of the two poles, where the temperature is relatively low. This effect is still further increased by the peculiar march of the aqueous vapour which is principally condensed about the poles, whence it returns to the equator by another way than that of the atmosphere, viz., along the surface of the earth in the liquid state.

The atmosphere cannot exactly follow the diurnal rotation. A half of its mass, or from about 30° lat. S. to 35° lat. N., lags somewhat behind, since all the molecules in this region being thrust upward describe circles continually increasing in size with the linear velocity from the lower level from which they started in their ascent. To this retardation must be superadded that of the surface trades resulting from their general flow towards the equatorial region. Beyond the tropics, on the contrary, in the temperate zones where the air advances into parallels of latitude continually diminishing in size, the other half of the atmosphere flows in advance of the earth's rotation. Towards the polar circles this advance is converted into a circling movement round the two poles from west to east.

The unequal distribution of land and water over the globe modifies this general aërial current, so that it does not flow on in one current, but is broken up into many currents—the equalities of the surface throwing the current of the counter-trades into several currents more or less distinct from each other. We can easily imagine the behaviour of the counter-trades by combining their march toward the poles with the two opposite transverse tendencies of which we are about to speak. Between the tropics, the resulting currents do not blow straight to the equator, but wear round more toward a westerly direction. Beyond the tropics, they do not blow directly toward the poles, but take a course inclined more to eastward. The two following figures will explain our meaning:—

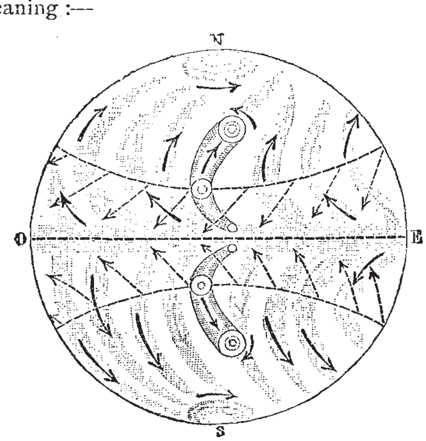

Fig. 13.

Fig. 13 represents the whole upper currents for both hemispheres on a projection of the meridian; and Fig. 14 for the northern hemisphere on a projection of the equator. The dotted arrows mark the surface counter-currents; in other words, the trade-winds blowing obliquely towards the equator, making nearly a right angle with the upper trades of the torrid zone. A slow whirling movement may also be seen around both poles resulting from the counter-trades. These really exist, for the meteorologists of the United States have recently described them under the name, a little fanciful, perhaps, of polar cyclones.

The aërial rivers which are marked out in the midst of these great movements, by which the equilibrium, incessantly disturbed, tends constantly to re-establish itself, exhibit then precisely the course which we have recognised as a peculiarity of the trajectories of cyclones, whilst the surface-trades have no relation to these same curves showing the courses of cyclones. This agreement is a further proof that cyclones must have their origin in the upper

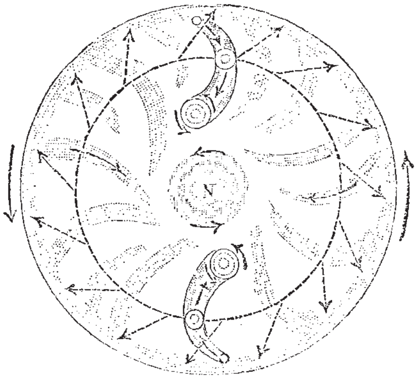

Fig. 14.

regions of the atmosphere, and thence descend even to the ground, and in doing so traverse strata of air either calm or in motion, in such a way as to be totally independent of the cyclone—a state of things incomprehensible on any other hypothesis that has yet been advanced. As to the direction of rotation of cyclones, it results from it that, in these currents strongly recurved, the velocity goes on diminishing transversely from the concave side to the convex side. The zone of calms would then no longer accord with the phenomena of an ascending updraught, but with a maximum of dilatation to the right and to the left of the place where the movement toward the poles commences. Lastly, the mean velocity of these currents, feeble at first in the neighbourhood of the equator, would go on accelerating just as the velocity of translation of our cyclones.

Segmentation of Cyclones.—Whatever may be thought of these opinions regarding the march of the upper trades, of which the surface-trades are the counterpart, it is impossible to doubt that cyclones take their origin from these currents. Let us then look more closely at these gyratory movements. If the maximum height of these trades be from 33,000 to 40,000 feet, and the lower diameter of the gyratory movements, or cyclones, where they meet the ground, from 120 to 180 nautical miles, it will be seen that cyclones must have a figure very different from waterspouts and tornadoes, whose proportions are altogether different, since the height of these last is enormously disproportioned to their lower diameter. Piddington was therefore right in comparing cyclones to mere whirling discs. It would however be more correct to regard them as waterspouts reduced to their upper funnel-shaped portion, or deprived of their slightly conical column, which descends even to the ground. As it advances, the generating current is lowered a little; the vertical height of the cyclone is thereby as much diminished, its section enlarges by contact with the ground, and the disc becomes even more flattened out.

This being granted, if any whirling movement encounters resistances, or if the general current exhibits differences of velocity in different places, it is in the upper regions of the atmosphere especially that these disturbing causes will act most powerfully on the phenomenon, because the velocities are there less, and the distances traversed by the currents enormous. Below, on the other

hand, where the column is narrowed to a very great extent, and where the velocity of the gyrations is excessive, the obstacles met with exercising little influence, are instantly reversed or overcome. Waterspouts acting by the lower extremity, at a distance from their funnel-shaped top (*embouchure*), undergo no change; but cyclones will not withstand the forces brought into play so easily.

Let the modifications thus induced by external causes be what they may, the preceding theory shows that they are possible, and that the rigorously circular movement enunciated by the authors of the "Laws of Storms" allows of perturbations more or less local, and more or less marked, for the simple reason that the whirling movements, which in the case of cyclones are reduced to their upper portions and are therefore little more than mere discs, are very easily modified. It is this, moreover, which explains the deviations from the rule that are found in even the earliest writings of the authors of the "Laws of Storms," as, for example, in Fig. 1 (vol. xii. p. 401), representing the Cuba hurricane, where, notwithstanding the general agreement of the arrows showing the wind with the purely circular theory of storms, there also occur several local deviations.

What can these perturbations be? How can a gyratory movement be changed under the influence of a given external cause? What happens if the velocities of the generating current undergo local changes? It would be as difficult to answer these inquiries *à priori* as it would have been to foresee, before the development of the mechanical theory of solid bodies, the astonishing results of an external force brought to bear on them; but the study of other whirling movements more within the reach of observation, and directed to the sun, has shown that a cyclone is not arbitrarily deformed in any manner whatever. Segmentation, or breaking up of the cyclone, is the last term of the alterations which it can undergo. Then the fragments into which it is broken up tend to assume the form of cyclones, each as perfect as the one from which they were formed, and they follow routes differing but little from each other and describing nearly the same trajectory, but at a distance from each other. This segmentation of cyclones occasionally occurs in the case of the thunderstorms which advance on France from the Bay of Biscay, of which the thunderstorm of the 9th of March, 1865, so well described by M. Marié-Davy, may be cited as an example. A like process of segmentation cannot take effect unless the primitive cyclone in some part and for some time deviate from its rigorously circular form. The tendency to keep this form maintains the ascendency sometimes, but if it begins to give way in a large cyclone, the result is a breaking up of the cyclone itself into segments.

It would be easy to adduce numerous cases in which whirlwinds, tornadoes, and cyclones appear in groups about a given point, or at least follow each other with rapidity. The evidence all goes to show that they are most frequently the result of the phenomenon of *segmentation*, so called from the term used in natural history to designate the process by which some of the lower animals are divided into segments each of which soon becomes a complete animal of itself. But it is in solar cyclones where this mysterious operation can be best followed step by step. Thus a circular sunspot may be seen gradually undergoing the process of deformation, then breaking up into parts, and ending by giving birth to other spots, which precede the original one in a row and at some distance, proceeding at the same pace and reproducing on a small scale the features and behaviour of the primitive type.

Conclusion.

The laws of storms, the statement of which in absolute terms ignores the modifications we have indicated, are therefore in reality only an approximate enunciation, just as are Kepler's laws, to which we have more than once compared them. Kepler's laws would be rigorously exact if we could leave out of account the action of the planets on each other and on the sun; but this being impossible, these laws are not an adequate expression of the truth. The same holds good with respect to the laws of storms. They would also be exact if the currents of the atmosphere never exerted any disturbing action, and as the laws take no account of these disturbing actions, and do not give the means of foreseeing them, or at least of measuring their effects, it would be a mistake to apply them blindly in practical affairs.

It was not by substituting the *cassinoïde* for Kepler's ellipse that science made progress; in like manner it will not be by the substitution of centripetal diagrams of storms for circular diagrams that navigation will be rendered safer. If we have succeeded in giving the true theoretical interpretation of these laws, it must be granted that the time has not come to abandon them, but rather to make them more complete.

To sum up, there are no centripetal waterspouts, whirlwinds, typhoons, or cyclones. The *moveable* forces of aspiration formed, as is said, over the heated ground of the tropics, do not transport themselves with their accompanying updraught to a distance of 700 or 800 leagues over the cold soil of high latitudes, and they have never determined the whirling movements of our atmosphere. The Laws of Storms are in general accord with the mechanical theory of these movements. The rules of navigation which are deduced from them, merit in ordinary cases the confidence sailors have had in them for the past thirty years. The exceptions should be only regarded as mechanical disturbances of the gyratory movement, the further study of which seems destined to complete a first and happy approximation to the truth. The discovery of the approximate laws of storms is one of the finest scientific conquests of this century, and if a closer approximation is to be made, it will be by a more careful study of solar cyclones.

Formerly whirling movements played an important part in our general conceptions of the universe. Fallen into disrepute by a very natural reaction from a false idea, they have been too much forgotten; therefore when at a later period a gyratory character was recognised in the great movements of the atmosphere, an effort was made with one consent to connect them with totally different causes. Geometricians seemed to class them among those irregular movements of which nothing could be made. We see, however, that movements of the cyclonic order constitute in truth a vast series of regular and stable phenomena, of which their perturbations even exhibit a behaviour in accordance with geometric principles. This series which begins with simple eddies in our streams of water, embrace the most singular as well as the most dreaded phenomena of the atmosphere, together with the vast movements which observation reveals in the sun, and extends even to the nebulæ, the structure of which Rosse's telescope has proved to be characterised by whirling movements. It is therefore most desirable that the theory of these movements should be again included in the domain of applied mechanics. The first step to this end is an empirical investigation of their laws, and this work the eminent authors of the "Laws of Storms" accomplished thirty years ago.

NOTES

Two members of the British Ornithologists' Union, Messrs. Harvie-Brown and Henry Seebohm, have recently returned from a most successful expedition into Northern Siberia. Leaving this country early in the spring of this year, they arrived at Ust Zylma, on the Petschora River, in the middle of April, after travelling overland from Archangel. They remained there